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The aim of research described herein was explore several fundamental problems in statistical data processing and system modeling, with particular aspects. The results obtained have almost completely been described in published journal and conference papers, so this report will focus on a summary of major results. The presentation will be in separate sections corresponding to the efforts of the co-principal investigators — T. Kailath, R. Gray, A. El Gammal and M. Morf:

1. Analysis of Nonstationary Signal Processes
2. Algorithms for Data Compression

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3. Reliable VLSI Computing Structures
4. Algorithms and Architectures for Statistical and Data Processing

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Final Technical Report
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Statistical Data Processing, System Modeling and Reliability

Thomas Kailath
Robert M. Gray
Abbas El Gamal
Martin Morf

The aim of research described herein was explore several fundamental problems in statistical data processing and system modeling, with particular aspects. The results obtained have almost completely been described in published journal and conference papers, so this report will focus on a summary of major results.

The presentation will be in separate sections corresponding to the efforts of the co-principal investigators -- T. Kailath, R. Gray, A. El Gamal and M. Morf:

1. Analysis of Nonstationary Signal Processes;
2. Algorithms for Data Compression;
3. Reliable VLSI Computing Structures; and
4. Algorithms and Architectures for Statistical and Data Processing.

1. Analysis of Nonstationary Stochastic Processes (T. Kailath)

Research Objectives

The goal of this project has been to develop a variety of signal processing algorithms with emphasis on nonstationary processes, reduced computationary demands and numerical stability.

Our research effort was directed along two main lines:

1. Characterization and parametrization of nonstationary processes based on the concept of displacement rank.

2. Developing new algorithms for a variety of problems in array processing, spectral estimation, and adaptive filtering.

Major Accomplishments

1. Modeling of Nonstationary Processes

The notion of displacement rank of a covariance was utilized to construct efficient parametrizations of nonstationary discrete-time second-order processes. Several distinct parametrizations were derived, all sharing a common set of *Schur coefficients*, which are a generalization of the well known *reflection* (or *partial correlation*) coefficients associated with stationary processes. The Schur coefficients, and an additional set of tapped-delay-line coefficients, serve as gains in lattice-form modeling and whitening filters for nonstationary processes. These lattice filters consist of *constant parameter* sections; the only time-variation required is the growth in time of the filter order.

The analysis of nonstationary processes with finite displacement rank illuminated the significance and versatility of the *Schur reduction* procedure. This analytical procedure, originally formulated by Schur (1917) for function-theoretic applications, has been since rediscovered several times in various disciplines. It occurs in network theory (as Darlington synthesis), in geophysical exploration (as dynamic deconvolution) and in numerical analysis (as fast Cholesky factorization). We have used it to compute the Schur coefficients of a given nonstationary covariance. Our analysis serves to clarify the relation between the numerous applications of the procedure and to extend it to multichannel cases. It also spurred a series of new results in the theory of inverse scattering.

Several specific classes of nonstationary processes emerged as generalizations of stationary processes. *Quasi-stationary processes*, which are obtained by linear time invariant (LTI) filtering of stationary processes, posses the same structural properties (including the same lattice models) as stationary processes. Dissipative processes, which include quasi-stationary as a particular case, have lattice models of higher complexity, but still share many properties of stationary covariances.

Another outcome of the analysis of nonstationary processes is the formulation of a unified theory of spectral analysis for such processes. Our results include as particular cases the previously developed theory of asymptotically stationary, asymptotically mean stationary and harmonizable processes. Our analysis provides also an attractive alternative to Wiener's generalized harmonic analysis for a broad class of nonstationary processes.

Several papers have been written on these topics, co-authored with B. Porat and H. Lev-Ari, with two major papers to appear in the *IEEE Transactions on Information Theory* in January 1984 and in September 1984 and another paper in the *IEEE Transactions on Automatic Control* in October 1983.

2. Algorithms for Detection and Estimation

The widely used adaptive lattice filters generate estimated innovations residuals of all orders up to a given maximum order, a feature that can be important in many identification and modeling applications. However, in many other adaptive-filtering applications, such as channel equalization and echo cancellation, the order of the desired estimation is known or upper-bounded a priori. In these cases, the lower order residuals are not really necessary, and further significant computational and implementational simplifications result when the adaptive filter directly computes the fixed-order residuals recursively in time. We have developed some new fast, fixed-order, exact-least-squares algorithms for tapped-delay-line adaptive filtering that algorithms require fewer operations per iteration and exhibit better numerical properties that the presently used Fast-Kalman algorithm of Morf, Ljung and Falconer [1978]. In comparison with the stochastic-gradient or LMS adaptive algorithm of Widrow and Hoff, the new new, fixed-order, least-squares algorithms yield substantial improvements in transient behavior at a modest increase in computational complexity. Additionally, over a wide range of practical applications, the new algorithms demonstrate numerical properties comparable to those of the normalized lattice.

In the course of these studies we expose an overnight in the initialization of the Fast-Kalman algorithm that often results in drastic deviation from true least-squares performance, and eventual divergence. We eliminate this problem in our approach, while obtaining an 80% reduction in complexity over the Fast Kalman algorithm during the initialization period, when initial conditions are zero. The insights of our geometrical derivation also aid in mitigating other finite-precision problems of the Fast Kalman algorithm. A [illegible] filter of [illegible] is guaranteed [illegible] are [illegible]. Finally, [illegible] simple modification of the new algorithms, and arbitrary weighting of the influence of these initial conditions through a soft-constraint is also permitted to reduce the effects of noise upon a good initial condition.

In related work, an efficient exact-least-squares procedure was developed for the adaptive adjustment of a fractionally spaced equalizer (FSE). Intersymbol interpolation of the desired training sequence is used by this new procedure to reduce computational requirements and to improve convergence. For a T/p FSE, a factor of p improvement in "start-up" time is attained ative to the multichannel FSE versions of the least-squares algorithms of Falconer and Ljung [1978] and of Satorius and Pack [1981]. Additional reductions in computational requirements are achieved by a special exact-least-squares modification for the passband "Nyquist" FSE structure of Mueller and Werner. The procedure is shown to be most efficiently implemented using a transversal-filter realization of the fast exact-least-squares algorithms. The *per-iteration* computational requirement of the new procedure (T/4 FSE) is found to be approximately the same as that of the more conventional, but much slower converging, (T/2) Tap-Leakage stochastic-gradient algorithms of Gitlin, Meadors, and Weinstein [1982]. Simulations have been conducted to verify the operation of the new procedure for both the training and decision-directed modes of operation.

3. Other Work

During the period of this contract, several papers based on work largely done in earlier years were submitted, or/and appeared in final journal form. They deal largely with [illegible] both deterministic and stochastic.

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2. Algorithms for Data Compression (R. M. Gray)

Research Objectives

The general goal of this project has been to develop computer-aided design algorithms for data compression systems and to study the relative performance, complexity, and rate of such systems. Where possible, comparisons have also been made with theoretical bounds and with traditional approaches. Particular emphasis has been placed on vector quantization (vector coding, block coding, multidimensional quantization) systems for speech waveforms, for linear predictive speech parameters, and for various random processes.

Major Accomplishments

As detailed in the annual reports and in the following list of publications, the research effort has been exceedingly fruitful in laying the groundwork for computer aided design of a variety of data compression systems. The algorithm of Linde, Buzo, and Gray (1980) for the design of locally optimum vector quantizers which was developed with the support of this contract has been extended both by our Stanford group and by a several other institutions to develop moderate complexity low rate and very low rate data compression systems for speech waveforms, voice coders, various random processes, and, most recently, images. Our group pioneered the basic algorithm and two of its most important variations: tree searched codes and product codes. In addition to the results of this research project, the basic techniques developed by this project have been used in other projects and other institutions for several new applications: New speech recognition systems based on vector quantization and not requiring dynamic time warping have been developed at the Naval Research Laboratory, the University of Mexico, Osaka University, and Bell Laboratories using variations on our algorithms. New low complexity image coding systems of rates less than one bit per pixel have been developed using our algorithms at the University of California, by our group, and by Mitsubishi Corp.

Part of the accomplishment of this project was the development of extensive software for vector quantizer design and data compression simulations. This software has been shared and extensively used by the Naval Research Laboratory.

During the final year of this contract the emphasis has been on the development of shape/gain vector quantizers, an example of product code quantization systems that operate in a memoryless fashion on successive data vectors and separately quantize a scalar gain term and a vector shape term. The quantizations are coupled by the distortion measure so that the encoder is optimal for codes with this structure. An iterative improvement algorithm was developed to yield locally optimum codes of the desired structure. The goal of this style of code is twofold: To provide better dynamic range by separately treating the energy and to provide a means of designing higher rate and hence better quality vector quantizers with reasonable computational complexity and memory requirements. These codes are capable of providing better performance for a fixed rate and complexity than the ordinary high complexity vector quantizers. Preliminary results for these systems were presented by Sabin and Gray (1983) and a paper has recently been submitted for submission for publication. A copy of this paper will be forwarded to the Air Force when complete as an epilogue to this final report.

With the exception of the final paper being prepared, all of the principal research results developed during the course of this project have been reported in the open literature. Preliminary portions of the final paper may be found in the conference proceedings of the paper by Sabin and Gray (1983).

With the termination of this contract, the image coding and the speech coding and recognition work will continued with the support of the Army Research Office and the Joint Services Electronics Program. Unlike the research reported here, the future research will focus on feedback vector quantizers and finite-state vector quantizers instead of the memoryless vector quantizers of this project. LSI and VLSI implementations of vector quantization systems with and without memory will be continued with the support of the Joint Services Electronics Program.

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3. Reliable VLSI Computing Structures (A. El Gamal)

Research Objectives

The following topics have been under investigation: (i) Coding for memories with stuck-at defects and random errors when the defect information is provided to the encoder or to the decoder. (ii) The improvement in storage capacity achieved by skipping defective or some partially defective memory cells. (iii) The complexity of encoding and decoding circuitry. (iv) The area and delay penalties involved in structuring VLSI arrays. (v) Communication complexity of computing.

Major Accomplishments

(i) Heegard [1] has examined a class of linear block codes (LBC) for improving the reliable storage of information in a computer memory with stuck-at defects and noise. He examined LBC's when the "side" information about the state of the defects is available to the decoder or to the encoder. In the former case, stuck-at cells act as erasures so that techniques for decoding the LBC's with erasures and errors can be employed. He introduced a class of modified linear block codes (MLBC's) to correct defects and errors when the location and nature of the defects is given to the encoder.

Theorem 1 of [1] characterizes the defect and error correction capability of LBC's and MLBC's in terms of minimum distances.

Theorem 4 states that MLBC's achieve capacity for a computer memory [illegible]

A class of modified cyclic codes was introduced in [1]. The BCH bound for these cyclic codes was derived and employed to construct MLBC's with specified bounds on the minimum distances.

(ii) In [2], the proposer and Greene considered a memory composed of N discrete cells, each characterized by a defect state s drawn independently according to $p(s)$. The probability of retrieving a symbol y given s and the stored symbol x is completely specified by $p(y \mid x,s)$. The selector identifies a subset of "good" cells, which alone are used to store data, in an effort to improve the reliable storage rate of the memory.

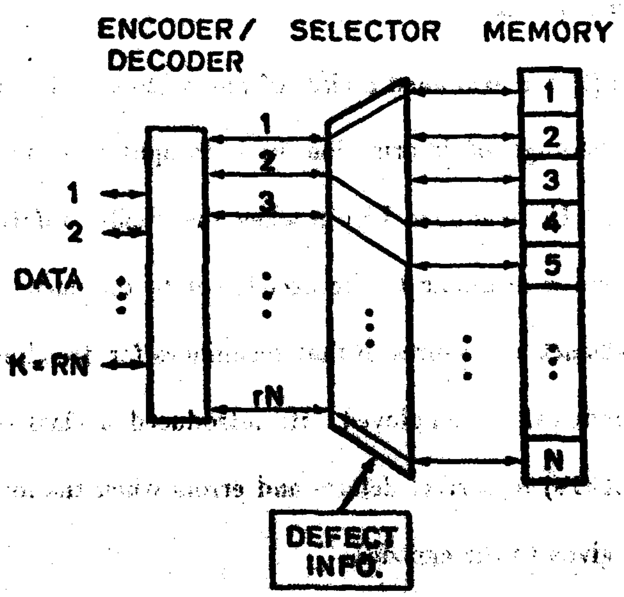

Fig. 1: Modified memory with a selector.

[illegible]

[illegible]

$u_i = 1$ if and only if the i^{th} cell is used. The symbols $[s_1,....,s_{rN}]$ are stored in order in the selected cells. A storage rate R is achieved if there exists a sequence of $(2^{RN},rN)$ codes, selection rules $p(\mathbf{u}\,|\,\mathbf{s})$ and decoding rules such that the probability error tends to zero.

The storage capacity is established for independent selection rules $p(\mathbf{u}\,|\,\mathbf{s}) = \prod_{i=1}^{N} p(u_i\,|\,s_i)$. It is then shown that the capacity is higher for the more general class of causal rules $p(\mathbf{u}\,|\,\mathbf{s}) = \prod_{i=1}^{N} p(u_i\,|\,s_i,....,s_i)$. However, for the cell consisting of two binary symmetric channels (BSC's), the capacity for causal rules is achieved by an independent rule. A similar result hold for any two-state cell when the state is known to the decoder.

For arbitrary selection rules, rates higher than those possible with causal rules are achievable, even for two-state BSC cells. The capacity for arbitrary rules is as yet unknown.

(iii) Ahlswede has proved the Elias [3] - Winograd [4] result for probability of error criterion. The capacity $\rightarrow e$ as $\frac{1}{c \log k}$, where k is the number of information bits, (results not written up).

(iv) In [5], the proposer and Greene investigated the asymptotic penalties of restructuring homogeneous VLSI arrays for yield enhancement. Each element of the fabricated array is assumed to be defective with independent probability p. A fixed fraction R of the elements are to be connected into a prespecified regular pattern with no defects. The probability of successfully connecting the pattern must be bounded away from zero as its size increases. Let d be the length of the longest connection and t be the number of wiring tracks needed to accomplish the interconnection. It is shown that:

(1) Connecting a chain of K elements from a linear array of N elements requires $d = \Omega(logN)$ and $t = 1$ track running parallel to the array.

(2) Connecting a linear array of K fixed I/O ports to distinct non-defective elements from a parallel array requires $d = \Omega(logN)$ and $t = \Omega(logN)$.

(3) Connecting K elements from an N-element linear array to K from a parallel N-element array, in pairs, requires only constant d and t.

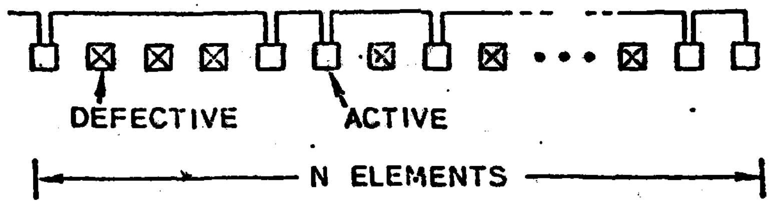

Fig. 2.a: Connection of a chain from an N-element linear array.

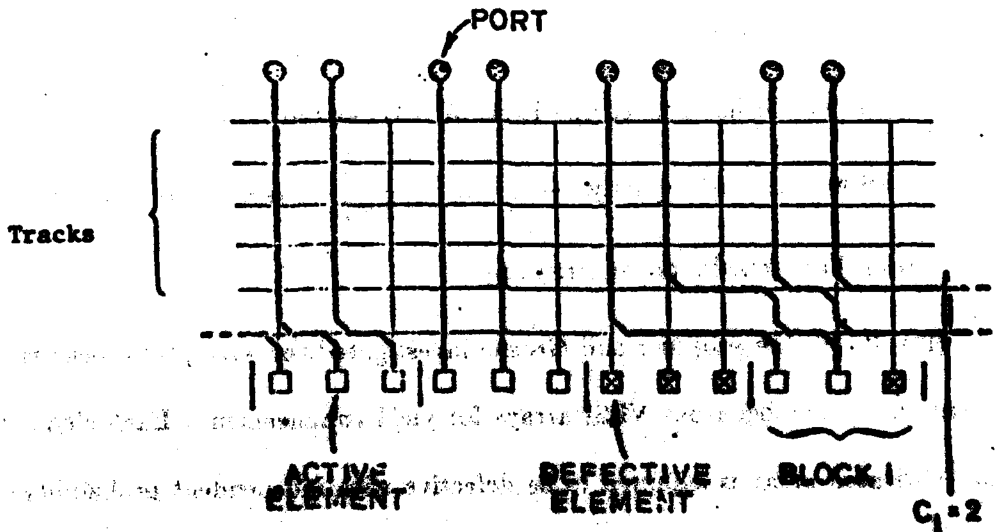

Fig. 2.b: A section of a selector.

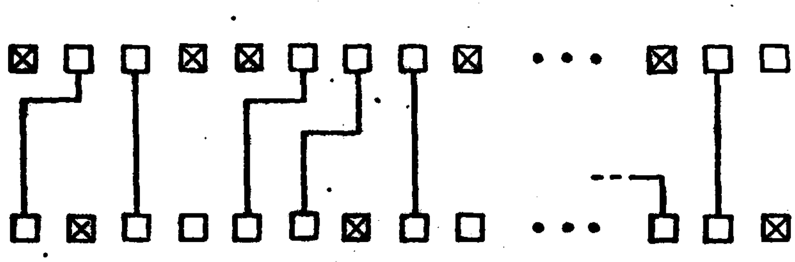

Fig. 2.c: Pairwise connection of two parallel N-element linear arrays.

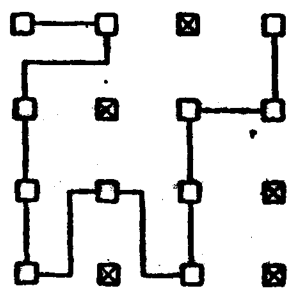

Fig. 2.d: Connection of a chain of $K=11$ elements from a 4×4 array

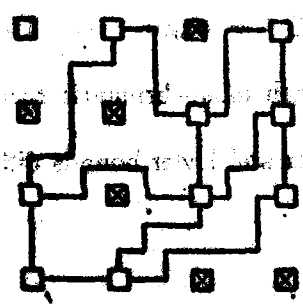

Fig. 2.e: Connection of a 3×3 square lattice from a 4×4 array.

(4) Connecting a chain of K elements from an $N \times X$ array requires constant d and one track between elements; this problem is closely related to the percolation problem of statistical physics.

In all the above cases, algorithms achieving the bounds on d and t are presented which connect the array with probability approaching one. The algorithms run in $O(n)$ time.

(5) Connecting a $K \times K$ square lattice from an $N \times N$ array is shown to require $d = \Omega\sqrt{(\log n)}$. In [6], it is shown that with $d = O\sqrt{(\log N)}$ only a constant number of tracks are needed. The proof employs the maximum flow-minimum cut theorem for graphs with random capacities.

(v) In [7], the proposer proved that if (X,Y) are two finite alphabet correlated sources with $p(x,y) > 0$ for all $(x,y) \in (\mathcal{X} \times \mathcal{Y})$, and if a function $F(X,Y)$ is α-sensitive, then the rate R of transmission from X to Y necessary to compute $F(X,Y)$ reliably must be greater than or equal to $H(X \mid Y)$. The same result holds if the function is highly sensitive and for every $x_1 \neq x_2 \in \mathcal{X}$, the number of elements $y \in \mathcal{Y}$ with $p(x_1,y) \cdot p(x_2,y) > 0$ is different from one.

(vi) Let $x,y \in \{0,1\}^n$. Persons X and Y are given x and y respectively. They communicate in order that both find the Hamming Distance $d_H(x,y)$ for any $x,y \in \{0,1\}^n$. In [8], the proposer and K. Feng show that $n + \log_2(n + 1-\sqrt{n}) \leq C(d_H) \leq n + \log_2(n+1)$. The lower bound proof uses upper bounds on the size of each monochromatic rectangle in the Hamming distance function table. The upper and lower bounds differ by at most one bit.

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4. Algorithms and Architectures for Statistical and Data Processing (M. Morf)

Professor Morf has moved to Yale University. He will be sending his portion of the final report directly.

However, a list of Ph.D. students partially supported under this contract, and a list of publications in the contract period are given here.

Ph. D. STUDENTS

Hadidi, M.T.	**"Contributions to the Analysis and Modeling of Multichannel Autogressive Stationary Processes," June 1983.**
Nehorai, A.	**"Algorithms for System Identification and Source Location," June 1983**
Delosme, J.M.	**"Algorithms for Finite Shift-Rank Processes," September 1982.**
Ahmed, H.	**"VLSI Architectures For Real-Time Signal Processing," June 1982**
Lee, D.T.L.	**"Ladder Form Realizations of Fast Algorithms in Estimation," August 1980.**

Published Journal (or book) Papers

J.-M. Delosme and Martin Morf, "Fast Algorithms for Finite Shift-Rank Processes: A Geometric Approach," published in the 1982 volume of the series on Published by *"Mathematical Tools and Models for Control Systems Analysis and Signal Processing,"* CNRS Editions, Paris, pp. 499-527. (invited)

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Accepted Papers

T. Kailath, L. Ljung, M. Morf, "Recursive Input-Output and State-Space Solutions for Continuous-Time Linear Estimation Problems," *IEEE Transactions on Automatic Control. (Accepted, revised and resubmitted)*

Published Conference Papers

J.-M. Delosme and M. Morf, "A Unified Stochastic Description of Efficient Algorithms for Second-Order Processes," *Proc. Workshop on Fast Algorithms for Linear Systems,* Aussois, France, September 21-25, 1981, pp. 13.1-13.22.

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M. Morf and D.T.L. Lee, "Recursive Square-Root Ladder Estimation Algorithms," *Proc. 1980 ICASSP,* Denver, CO, April 9-11, 1980, pp. 1005-1017.